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14. ABSTRACT
A driving simulator was used to examine the relationship between motion perception and driving performance. Although motion perception test scores have been shown to be related to driving safety, it is not clear which combination of tests are the best predictors and whether motion perception training can improve driving performance. In Experiment 1, 60 younger drivers (22.4 ± 2.5 years) completed three motion perception tests [2D motion-defined letter (MDL) identification, 3D motion in depth sensitivity (MID), and dynamic visual acuity (DVA)] followed by two driving tests [emergency braking (EB) and hazard perception (HP)]. In Experiment 2, 20 drivers (21.6 ± 2.1 years) completed 6 weeks of motion perception training (using the MDL, MID and DVA tests) while 20 control drivers (22.0 ± 2.7 years) completed an online driving safety course. EB performance was measured pre- and post-training. In Experiment 1, both MDL (r=.34) and MID (r=.46) significantly correlated with EB score. The change in DVA score as a function of target speed (i.e., "velocity susceptibility") was most strongly correlated with HP score (r=-.61). In Experiment 2, the motion perception training group had a significant decrease in brake reaction time on the EB test from pre-post while there was no significant change for the control group: t(38)=2.24, p=0.03. Tests of 3D motion perception are the best predictor of EB while DVA velocity susceptibility is the best predictor of hazard perception. Motion perception training appears to result in faster braking responses.

15. SUBJECT TERMS
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Motion Perception and Driving: Predicting Performance Through Testing and Shortening Braking Reaction Times Through Training

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PURPOSE. A driving simulator was used to examine the relationship between motion perception and driving performance. Although motion perception test scores have been shown to be related to driving safety, it is not clear which combination of tests are the best predictors and whether motion perception training can improve driving performance.

METHODS. In experiment 1, 60 younger drivers (22.4 ± 2.5 years) completed three motion perception tests (2-dimensional [2D] motion-defined letter [MDL] identification, 3D motion in depth sensitivity [MID], and dynamic visual acuity [DVA]) followed by two driving tests (emergency braking [EB] and hazard perception [HP]). In experiment 2, 20 drivers (21.6 ± 2.1 years) completed 6 weeks of motion perception training (using the MDL, MID, and DVA tests), while 20 control drivers (22.0 ± 2.7 years) completed an online driving safety course. The EB performance was measured before and after training.

RESULTS. In experiment 1, MDL ($r = 0.34$) and MID ($r = 0.46$) significantly correlated with EB score. The change in DVA score as a function of target speed (i.e., "velocity susceptibility") was correlated most strongly with HP score ($r = -0.61$). In experiment 2, the motion perception training group had a significant decrease in brake reaction time on the EB test from pre- to posttreatment, while there was no significant change for the control group: $t(38) = 2.24$, $P = 0.03$.

CONCLUSIONS. Tests of 3D motion perception are the best predictor of EB, while DVA velocity susceptibility is the best predictor of hazard perception. Motion perception training appears to result in faster braking responses.

Keywords: driver testing, motion perception, driver behavior

The ability to detect and discriminate one's own motion, and the motion of other vehicles and pedestrians in the environment is critical for driving safety. Examples of driving tasks that depend on precise and accurate motion perception include controlling one's speed and heading when entering a curve,[1] judging whether it is safe to overtake and pass another vehicle,[2] responding to a lead vehicle suddenly braking,[3] and detecting pedestrian incursions in the roadway.[4] Even relatively small impairments in motion perception are likely to increase crash risk significantly.[5] Given the essential role that motion perception has in driving, it has been hypothesized that simple tests of motion perception may be predictive of driving ability and accident risk.[6] Over the past decade, a small number of studies have provided strong support for this hypothesis, demonstrating correlations between a variety of motion perception measures and indices of driving performance.

To date, the most commonly used measures of motion perception have involved motion sensitivity (i.e., quantifying the smallest amount of movement needed to indicate the direction of movement accurately). An important distinction that has been identified in such tests is the stimulus resolution. Some previous studies have used small, high resolution (i.e., high spatial frequency) moving random dot patterns as test stimuli,[6,7] while others have used coarse, low resolution (i.e., low spatial frequency) moving gratings.[8] While both sets of tests have been found to be correlated with measures of driving performance/safety, such as hazard perception tests scores and self-reported attentional failures during driving, it recently has been shown that the relationship between driving performance and motion perception for high resolution tests can be explained fully by other visual abilities, namely acuity and contrast sensitivity.[9] Therefore, tests using high resolution stimuli may not provide a good means of assessing the role of motion perception in driving.

Another test that has been used previously in this area is dynamic visual acuity (DVA), where an object must be identified (or object feature localized) while the object is in motion. Therefore, the ability to perceive motion and the ability to track the target with eye movements are assessed. The general finding from this research is that DVA is a better predictor of driving performance than static visual acuity (VA), but is weaker than other measures of motion perception.[6,10]

One of the limitations of previous research examining the relationship between DVA and driving performance is that the effect of target speed was not analyzed in detail. Previous research in other domains, namely sports, has shown that this

may be important for predicting visual-motor performance. For example, in a study of catching performance, it was found that skilled catchers had a DVA that decreased only slightly as target velocity was increased (what the authors termed "velocity resistance").[11] Conversely, less-skilled catchers showed a more dramatic decline in DVA as a function of target velocity (what the authors termed "velocity susceptibility"). A similar relationship between DVA and performance also has been reported for other sports.[12] One of the goals of our study was to determine whether velocity resistance/susceptibility relates to driving performance.

Another limitation of previous research in this area is that the relationship between motion perception tests and driving performance has been examined only for frontoparallel (2-dimensional [2D]) motion (i.e., up/down or left/right). Very few previous experiments in this area have used tests of motion-in-depth (3D) perception (i.e., towards/away). We feel that this is an important omission for several reasons. First, for many of the driving situations in which a large number of accidents occur (e.g., rear-end collisions and across-path turns) the primary type of motion involved is 3D motion. Second, previous research has shown that older drivers can have impairments in their ability to judge approaching motion.[5,13,14] Finally, and most critically, it has been demonstrated that 2D and 3D motion are processed in different brain regions, and individuals can have a selective impairment for one type of motion.[15,16] For example, previous research has reported cases of "motion in depth blindness" in which individuals fail to detect approaching/receding motion in certain locations of their visual field while detection of 2D motion is normal.[17] These findings suggest that tests of 2D motion perception may not be predictive of driving ability in some tasks.

To our knowledge, only one previous study has investigated the relationship between tests of 3D motion perception and driving performance.[18] In that study, 2D speed discrimination, 3D speed discrimination, estimation of time to collision for 3D (approaching) motion, and heading discrimination were measured. Scores on these tests were related to self-reported driving difficulties and accidents. Significant relationships between driving difficulty ratings and scores were found for all tests except 3D speed discrimination. However, several participants who reported no driving difficulties also scored poorly on the motion perception tests. As recognized by the authors, the dependent variables used may not have been sensitive enough to pick up differences between these tests and further research measuring actual driving performance is needed. It also has been reported that velocity discrimination for motion in depth (expanding radial pattern) was correlated with several measures of student pilot performance in flight tests as well as flight simulations.[19,20] Thus, motion perception tests also may have selection and training applications in aviation, as well as for driving.

From this brief review, it is clear that more research is needed to identify the combination of motion perception tests that will be most predictive of driving ability. The goal of our study was to expand on this effort by directly comparing the relationship between 2D and 3D motion perception tests and driving performance; investigating the relationship between target speed, DVA and driving performance; and directly comparing motion perception tests with other visual tests (with static stimuli) that have been shown to be related to driving safety. Another aspect of the relationship between motion perception and driving performance that has not been studied in previous research is whether motion perception training can improve driving ability. Recent research has shown that training on simple perceptual-cognitive tests can improve driving performance and reduce accident risk.[21] Therefore, in experiment 2 of our study our goal was to

evaluate to what extent training on motion tests can improve driving performance.

The aim of experiment 1 was to investigate the relationship between performance on a set of motion sensitivity tests and performance on a set of tests of driving performance in a simulator. As discussed above, we included 2D and 3D motion perception tests, and a DVA test, which required observers to track visually moving targets moving at different speeds. To allow for comparison, we also included tests of VA, contrast sensitivity and the Useful Field of View (UFOV[22]). The driving tests included an emergency braking test and a hazard perception test. The experiment was designed to test the following hypotheses:

- There would be a significant correlation between the 3D motion test and the emergency braking test, because this driving task primarily involves detection of 3D (looming) motion. The relationship between the 2D test and EB, and between the DVA test and the EB would not be significant.
- The 2D motion and DVA test would be correlated significantly with the HP as has been found in previous research described above.
- For the DVA test, "velocity susceptibility" (as assessed by the relationship between DVA threshold and target speed) would be related significantly to performance on the HP test.

In experiment 1, we found significant relationships between different tests of motion perception and two tests of driving performance. The aim of experiment 2 was to investigate the effect of motion perception training on driving performance in a simulator in comparison with a control group that received standard, text-based driver training. The experiment was designed to test the following hypothesis: drivers in the motion perception training group should show a significantly greater improvement in driving performance (pre–post training) as compared to the control group.

METHODS

Experiment 1

Subjects. We recruited 60 subjects (42 male, 18 female; mean age, 22.4 ± 2.5 years) from the Birmingham, UK area. Participants received payment for their participation. All participants had a full valid UK driving license and had no obvious visual deficits that would affect their driving ability at the time of testing. Participants were asked to wear any prescribed lenses (i.e., glasses or contacts) during testing, but were not given any additional refractive correction. Driving experience was quantified as the number of years since driving license was awarded. All participants had a minimum of 6 months of driving experience. The work reported here was approved by the Science, Technology, Mathematics, and Engineering (STEM) Ethical Review Committee at The University of Birmingham, and adhered to the tenets of the Declaration of Helsinki. All participants signed a consent form.

Apparatus. *Motion Perception Tests.* The motion perception tests used custom-designed software. Tests were displayed on a Philips Brilliance 107P40 VGA 120 Hz CRT monitor (Philips, Eindhoven, The Netherlands), which subtended 40 (H) × 36 (V) degrees of visual angle at a resolution of 1920 × 1440 pixels. The viewing distance was 57 cm. Three tests were used: the motion-defined-letter test (MDL), the motion-in-depth-sensitivity test (MIDS), and the DVA test (DVA).

The MDL test, a 2D motion perception test, was based on the work of Hong and Regan.[17] On each trial the participant is
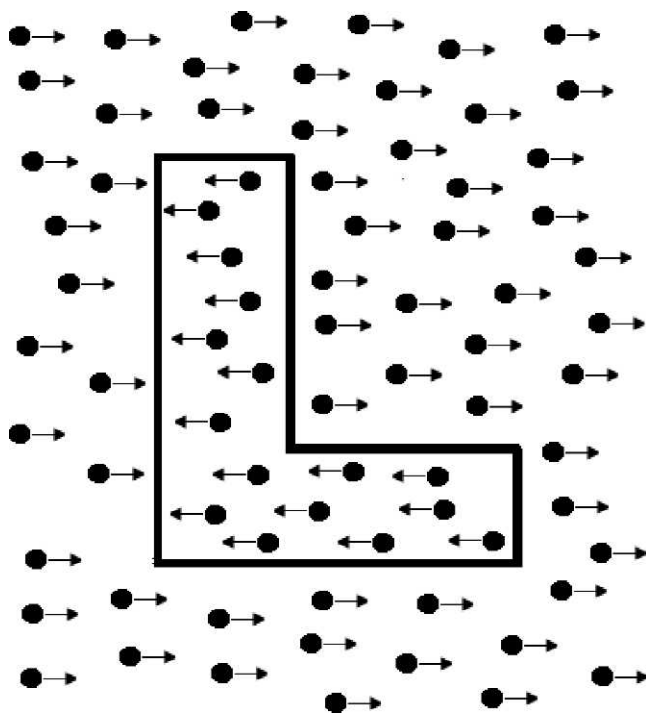
FIGURE 1. Illustration of an MDL. The *dots* inside and outside the boundary of the letter moved in opposite directions at the same speed. Note the *solid black border* was not visible in the actual test.

presented with a display of 1200 moving white dots presented on a black background. Each dot was comprised of 4 pixels and had a luminance contrast of 92%. As illustrated in Figure 1, a letter is made visible by moving the dots inside the letter boundary in the opposite direction to the dots outside of the letter boundary. The entire display of dots subtended $15° \times 15°$ of visual angle, while the letters subtended $7° \times 7°$. The dot density was identical inside and outside the letter boundary. The dots inside and outside the letter boundary always moved at the same speed with the direction of motion chosen randomly on each trial. The letter could be made more (or less) visible by increasing (or decreasing) the motion contrast (relative velocity). On each trial the letter was chosen randomly from nine possible alternatives (C, D, E, F, L, O, P, T, and Z) and participants were asked to identify the letter by pressing a key on the numerical keypad on a standard keyboard. The standard keys were covered with labels corresponding to each of the letters. The presentation duration was 0.5 seconds.

A maximum-likelihood adaptive staircase psychophysical procedure (ML-PEST) was used to adjust the speed of the dots on each trial based on the participant's responses. A correct identification resulted in a reduction in dot speed while an incorrect response resulted in an increase in dot speed. The initial dot speed was $1°/s$ and the step size was $0.2°/s$. The step size was halved after the first two reversals. Four staircases were interleaved randomly so that participants could not anticipate the dot speed on each trial. After a minimum of 6 reversals for each staircase the test concluded, with the average speed of the final four reversals used to calculate the participant's MDL threshold for each letter size. The thresholds for the four staircases then were averaged to generate the observers' MDL threshold in deg/s.

The MID test, a 3D motion perception test, involved the presentation of two radially expanding flow fields—with differing velocities—on each trial. The flow fields were

comprised of 1500 white dots presented on a black background and the duration of each presentation was 1 second. The interpresentation interval was 0.2 seconds and the intertrial interval was 0.5 seconds. Participants were required to make a two-alternative forced-choice judgement (2AFC) about which presentation the movement velocity was greater by pressing one of two response keys on the keyboard. The velocity of one of the presentations (the reference) was held constant throughout the test and had a value of $5°/s$. The velocity on the other presentation (the test) was adjusted in accordance with an ML-PEST staircase procedure. The order of the test and reference presentation was chosen randomly on each trial. The initial difference in velocity of the test presentation was $0.5°/s$ and the step size was $0.1°/s$. The step size was halved after the first two reversals. Four staircases were interleaved randomly so that participants could not anticipate the dot speed on each trial (i.e., if they indicated the test was faster than the reference the test presentation on the next trial would not necessarily be slower). After a minimum of 6 reversals for each staircase the test concluded, with the average speed of the final four reversals used to calculate the participant's MID threshold for a given staircase. The thresholds for the four staircases then were averaged to generate the observers' mean MID threshold in deg/sec.

On each trial of the DVA test, a white Landolt C target moved across a grey background. The target had a contrast of 50% relative to the background. The orientation of the notch in Landolt C target was chosen randomly for each trial from one of four alternatives (up, down, left, right). The target always initially appeared in the center of the display and the presentation duration was 1.0 second on all trials. The movement direction was chosen randomly from the 8 cardinal directions. The participant's task was to make a 4AFC judgment about the notch orientation by pressing one of the four arrow keys on the numerical keypad of a standard keyboard. The notch size was adjusted according to a ML-PEST staircase procedure. The initial notch size was 100 arc min and the step size was 30 arc min. The step size was halved after the first two reversals. Four staircases (corresponding to four target speeds: $5°$, $10°$, $15°$, and $20°/s$) were interleaved randomly. Four speeds were used so that "velocity resistance"[11] could be measured. Speed was constant within a given trial (i.e., the target did not accelerate). After a minimum of 6 reversals for each staircase the test concluded, with notch size of the final four reversals used to calculate the participant's DVA threshold for each velocity in arc min. We also calculated an overall threshold (designated DVA below) by calculating the mean for the 4 velocities.

VA and Contrast Sensitivity Test. The VA and contrast sensitivity were measured using the Freiburg Visual Acuity + Contrast test.[23] The VA data were collected in decimal form, transformed to LogMAR units. Contrast sensitivity is based on a single optotype size of varying contrast . The Freiburg software is available in the public domain at http://www.michaelbach.de/fract/index.html.

UFOV Test. The commercially available UFOV test was used (Visual Awareness Research Group, Inc., Punta Gorda, FL). Only data from subtest 2 were collected, because previous research has shown it to be the most predictive of driving safety.[7] The UFOV 2 test measures divided attention: The subject is asked to identify a central presented object (an image of a car or a truck) and localize a car that is presented simultaneously in the periphery. The presentation duration is adjusted using a staircase procedure. The score for this test is the presentation duration (in milliseconds) for which 75% correct performance is achieved.

Driving Tests. The driving tasks were carried out on an XPI Simulation Limited XPDS-XP300 driving simulator, version 2.2. The simulator was comprised of a Logitech G25 Racing Wheel/ Pedals (Logitech, Newark, CA) and three Microsoft Plug and Play monitors (Microsoft, Redmond, WA) with 43.2 cm displays (2840 × 1025 resolution). The system ran using the NVIDIA GeForce GTS 450 graphics card (NVIDIA, Santa Clara, CA) with a 1024 MB memory. Participants positioned themselves so they could use the steering wheel and pedals comfortably, and such that their eyes were 80 cm away from the computer monitors. Two driving tests were used: Emergency Braking (EB) and Hazard Perception (HP).

In the EB test, the lead vehicle began from a stopped position and accelerated to a speed of 40 miles per hour (mph). It then travelled at speed ranging between 35 and 45 mph with speed changes every 5 seconds on average. At a random time interval (between 40–180 seconds after the beginning of the trial) the lead car braked suddenly with a −6 m/s^2 deceleration rate. Drivers were instructed to accelerate to catch up with the lead vehicle and then maintain a 2-second time headway. If their time headway was larger than 3 seconds, the trial was aborted and rerun. The brake lights of the lead vehicle were deactivated. Drivers were instructed further that they must brake to avoid collision with the lead vehicle and must not go out of the lane (any trials for which this occurred were discarded and rerun).

In the HP test participants were required to indicate, using a button on the steering wheel, when they perceived there to be a hazard during 3 different driving scenarios. Across the 3 scenarios there were a total of 10 potential driving hazards: construction vehicle pulling out of work site from left, construction vehicle pulling out of work site from right, child pedestrian crossing street in school zone from left, child pedestrian crossing street in school zone from right, adult pedestrian crossing the street from left, adult pedestrian crossing the street from right, vehicle emerging from side street on the left, vehicle emerging from side street on the right, vehicle ahead waiting to turn across traffic, and vehicle ahead reversing. Each scenario involved driving through an urban environment at a speed of 35 mph for 5 minutes with the hazards placed randomly throughout. If the participant pressed the button when the hazard was visible and correctly verbalized the nature of the hazard to the experimenter it was scored as a correct response. If the participant pressed the button when no hazard was visible it was scored as a false alarm. The HP score for each driver was the number of hazards identified successfully minus the number of false alarms. We chose to calculate the score in this manner so that it provided an unbiased measure of HP performance, that is, the drivers' criteria for indicating the presence of hazards also was taken into account. Drivers were presented with a list of the potential hazards before completing the test.

Procedure. Each participant completed the vision tests followed by the two tests of driving ability. The order of driving tests was counterbalanced across participants. Participants were given a practice period of two minutes of free driving through a city environment to familiarize themselves with the driving simulator before beginning the tasks. Likewise, a 30-second practice period was allowed before each visual test for the participant to understand the tests fully.

Data Analysis. The SPSS software (version 19; SPSS, Inc., Chicago, IL) was used to analyze the data. Initial screening was administered to identify any outliers. Pearson's correlations were first calculated between each of the tests. We next performed stepwise multiple regression to determine whether combinations of the motion tests best predicted driving performance. Velocity resistance/susceptibility for the DVA test was determined by plotting DVA threshold as a function of target speed, fitting a linear curve to the data and calculating slope. Slopes were used as an additional variable in the multiple regression analyses.

Experiment 2

Subjects. A total of 40 subjects (28 males and 12 females) completed experiment 2. Participants in the experimental group (15 males, 5 females) had a mean age of 21.2 ± 2.1 years, while subjects in the control group (14 males, 6 females) had a mean age of 22.0 ± 2.7 years. All subjects had a full valid UK driving license and had no obvious visual deficits that would affect their driving ability at the time of testing. All participants received payment for their participation. The work reported here was approved by the Science, Technology, Mathematics and Engineering (STEM) Ethical Review Committee at The University of Birmingham, and adhered to the tenets of the Declaration of Helsinki. All participants signed a consent form.

Apparatus and Procedure. The apparatus and procedure were as described in experiment 1 except for the following. The experiment was divided into 8 phases: a pretest, six training blocks (once per week), and a posttest. Participants were allocated randomly to either the experimental or control group. During the pretest, all participants completed all of the visual tests used in experiment 1 and the EB driving task. During the posttest all participants completed the EB task. In the pre- and posttests the EB task was repeated 5 times for each participant and the average braking response time was calculated. During each of the training blocks, participants in the experimental group ($n = 20$) completed the three motion tests used in experiment 1 in random order. Each block lasted roughly 30 minutes. To create a training scenario, auditory feedback was added to each of the tests in experiment 2 and the threshold was displayed at the end of each trial. Participants in the control group ($n = 20$) completed an online driving safety course that involved reading about rules and regulations (available in the public domain at https://www.gov.uk/highway-code) and answering multiple choice questions (and receiving feedback about the accuracy of their response) during the training blocks (available in the public domain at https://www.gov.uk/practise-your-driving-theory-test). Neither of the groups performed simulated driving during the training blocks.

Data Analysis. Separate repeated measures ANOVA was used to examine the changes in the 3 motion-perception test scores over time for the experimental group. To analyze performance on the EB driving test a 2 × 2 mixed-factorial ANOVA was used with Group (experimental, Group) as the between-subject factor and Test Phase (Pre, Post) as the within-subjects factor.

RESULTS

Experiment 1

Table 1 shows the descriptive statistics for the visual and driving tests. Bivariate correlations between visual and driving tests are shown in Table 2. For the EB driving test, better driving performance (i.e., shorter brake reaction time) was associated significantly with better performance on the MDL test (i.e., lower threshold), better performance on the MID test (i.e., lower threshold), higher VA, and higher contrast sensitivity. Note that the VA measure is a threshold, so a lower score represents higher acuity. The scatter-plots for the three strongest predictions of EB performance are shown in Figure 2. The stepwise regression analysis performed on the EB data revealed that three significant predictors accounted for approximately 33% of the variance: ($F[3,59] = 9.5$, $P < .001$).

TABLE 1. Descriptive Statistics for the Visual and Driving Tests in Experiment 1

Variable	Minimum	Maximum	Mean	SD
Age	18	26	22.4	2.36
EXP	0.5	8	4.19	2.11
MDL, deg/s ↓	0.07	0.20	0.13	0.04
MID, deg/s ↓	0.03	0.22	0.12	0.06
DVA, arc min ↓	7.8	81.6	33.9	17.9
DVA slope ↓	0.23	1.72	0.86	0.42
Log MAR acuity ↓	−0.21	0.11	−0.07	0.09
Log CS ↑	1.6	1.99	1.80	0.12
UFOV2, ms ↓	36	89	49.6	14.2
EB, s ↓	0.62	1.9	1.09	0.32
HP, /10 ↑	1	10	5.71	3.13
HP hits ↑	6	10	8.3	1.52
HP FA ↓	0	6	2.81	1.33

Arrows are used to indicate whether a higher (↑) or lower (↓) score represents better performance for a particular test. EXP, years of driving experience; DVA slope, slope of DVA threshold × target speed fit; Log CS, contrast sensitivity; HP hits, instance in which the driver correctly identified a potential hazard; HP FA, false alarms, instance in which the driver incorrectly indicated a hazard was present.

The three predictors were MID threshold ($\beta = 0.36$, $t = 3.2$, $P < .01$), log contrast sensitivity ($\beta = −0.26$, t = 2.4, $P < .05$), and LogMAR acuity threshold ($\beta = 0.24$, $t = 2.2$, $P < .05$).

For the HP test, a greater ability to identify hazards (i.e., higher score) was associated significantly with better performance on the DVA test (i.e., lower threshold), a lesser effect of speed on DVA performance (i.e., lower DVA threshold × target speed slope), higher VA, better performance on the UFOV2 test (i.e., lower presentation threshold), being older, having more years of driving experience, and higher contrast sensitivity. The scatter-plots for the three strongest predictions of HP performance are shown in Figure 3. The stepwise regression analysis performed on the HP data revealed that three significant predictors accounted for approximately 47% of the variance: ($F_{[3,59]} = 17.8$. $P < .001$). The three predictors were DVA threshold × target speed slope ($\beta = −0.44$, $t = −4.9$, $P < .001$), UFOV 2 score ($\beta = −0.44$, t = −5.0, $P < .001$), and log contrast sensitivity ($\beta = 0.21$, $t = 2.5$, $P < .05$).

Experiment 2

Pretest Comparison. Table 3 shows the descriptive statistics for the visual tests completed at the pretest stage. Data are separated for the experimental and control groups.

Independent samples *t*-tests revealed marginally significant differences between the two groups for MDL score ($t_{[38]} = −2.06$, $P = 0.05$) and UFOV score ($t_{[38]} = 1.96$, $P = 0.06$). All other comparisons were not significant (P all > 0.1).

Changes in Motion Perception. Figure 4A shows the means and standard deviations for the three motion-perception tests at each of the six weeks of training for the experimental group. The repeated-measures ANOVAs indicated significant effects of training for MDL ($F_{[5, 95]} = 17.4$, $P < 0.001$), MID ($F_{[5, 95]} = 33.2$, $P < 0.001$), and DVA ($F_{[5,95]} = 3.28$, $P = 0.013$). These findings generally are consistent with previous research demonstrating that motion perception can improve with training.[24]

Effect of Training on Driving Performance. Figure 4B shows the mean EB time for the two groups in the pre- and post-tests. The 2 × 2 mixed factors ANOVA revealed a significant main effect of test block ($F_{[1, 38]} = 11.9$, $P = 0.01$), and a significant interaction effect between group and block ($F_{[1, 38]} = 4.2$, $P = 0.04$). As can be seen in Figure 4B, this effect was due to the fact that the motion test training group showed a larger improvement in driving performance. A post hoc comparison revealed that the mean EB time was significantly lower in the posttest for the experimental group compared to the control group: $t_{(38)} = 2.24$, $P = 0.03$.

To investigate further the relationship between the training on the motion perception tests and driving performance, we calculated the pre–post change in motion test score for the motion tests. We next calculated bivariate correlations between changes in motion test scores and the change in braking time. This analysis revealed a significant positive correlation between change in braking time and change in MID score ($r = 0.47$, $P < 0.05$). The correlation was not significant for either MDL ($r = 0.26$, $P > 0.05$) or DVA ($r = 0.1$, $P > 0.05$).

DISCUSSION

Experiment 1

Experiment 1 was designed to expand on previous research examining the relationship between motion perception and driving performance. Our first goal was to compare directly 2D and 3D motion tests. As predicted, scores on the 3D motion test were correlated significantly with performance in the emergency braking task and this test had the highest correlation of all vision tests. We hypothesized that the 3D motion tests would be related more strongly to driving performance, in this case because emergency braking in a car following situation primarily involves the detection of 3D

TABLE 2. Bivariate Correlations Between Motion Perception and Driving Performance in Experiment 1

Variable	HP ↑	Age	MDL ↓	MID ↓	DVA ↓	DVAs ↓	VA ↓	CS ↑	UFOV ↓	EXP
EB ↓	−0.26	−0.15	0.34*	0.46*	0.09	0.14	0.34*	−0.33†	0.23	−0.12
HP ↑		0.27†	−00.06	−0.16	−0.33*	−0.61*	−0.32†	0.28†	−0.60*	0.29†
Age			0.15	0.21	0.17	0.12	0.13	0.-19	0.19	0.91*
MDL ↓				0.23	0.06	−0.16	0.16	−0.16	−0.06	0.06
MID ↓					−0.18	0.05	0.22	−0.15	0.13	−0.2
DVA ↓						0.31†	0.12	−0.19	0.25	−0.08
DVAs ↓							0.17	−0.12	0.33*	−0.04
VA ↓								−0.29†	0.20	0.01
CS ↑									−0.14	0.01
UFOV										0.02

Arrows are used to indicate whether a higher (↑) or lower (↓) score represents better performance for a particular test. DVAs, slope of DVA threshold × target speed fit; VA, LogMAR acuity; CS, contrast sensitivity.

* $P < 0.01$.

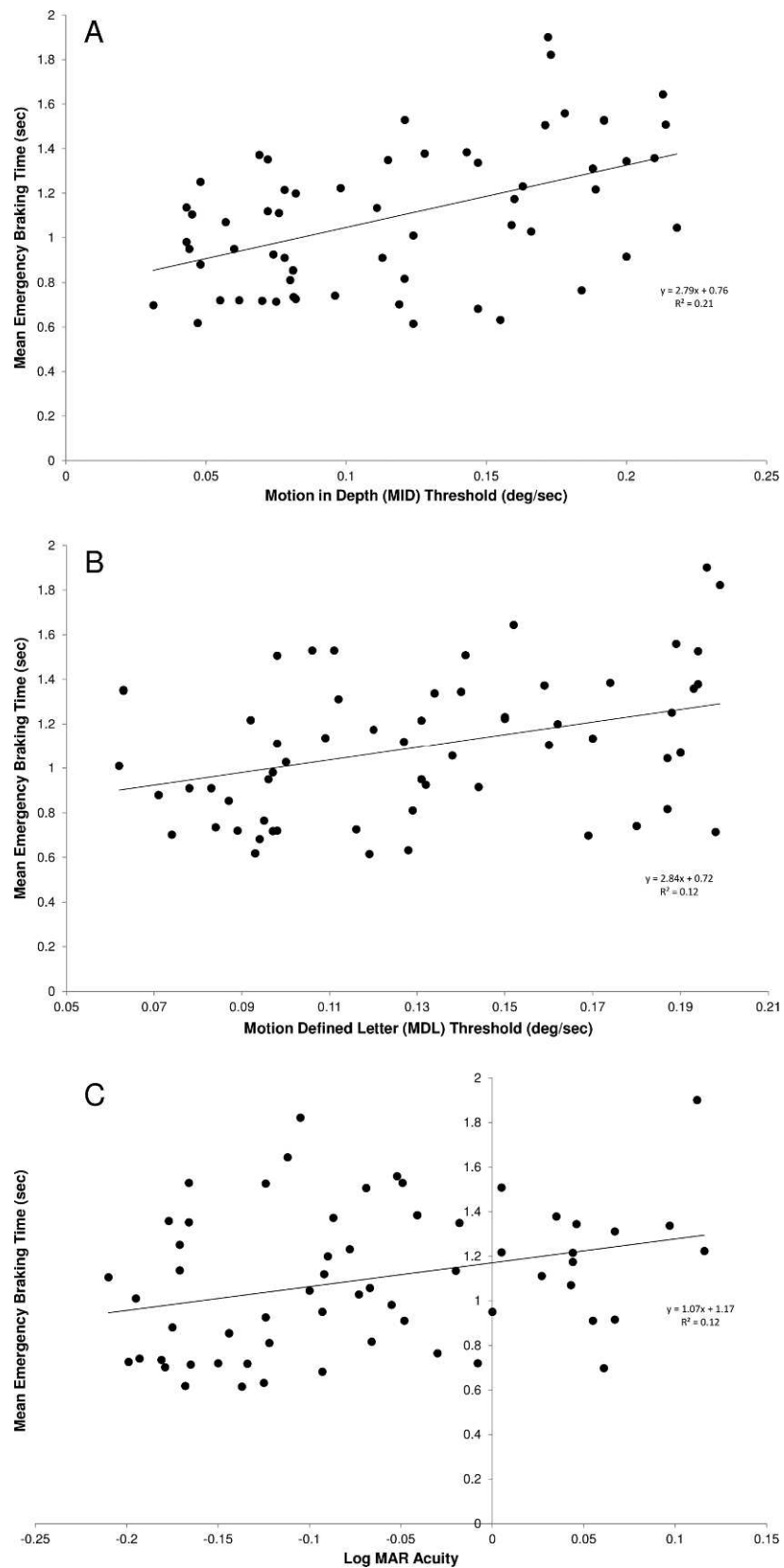† $P < 0.05$. All other correlation not significant.

FIGURE 2. Scatter-plots for test scores most strongly related to emergency braking time.
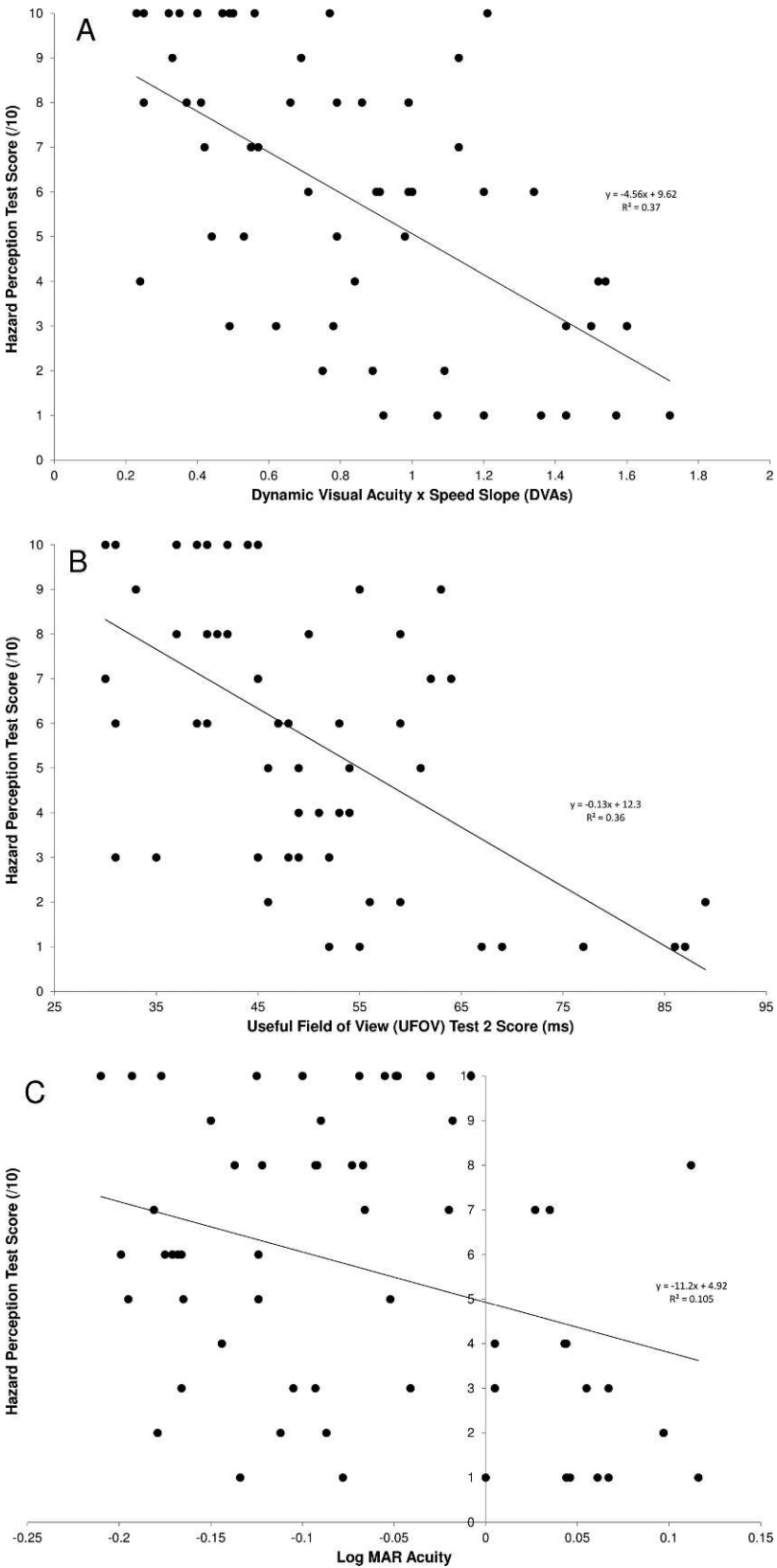
FIGURE 3. Scatter-plots for test scores most strongly related to hazard perception test score. Hazard perception scores were the number of hits minus the number of false alarms.

TABLE 3. Descriptive Statistics for the Visual Pretests in Experiment 2

Variable	Minimum	Maximum	Mean	SD
Control group				
Age	18	26	22.0	2.71
EXP	0.5	5	3.9	2.4
MDL, deg/s ↓	0.06	0.19	0.12	0.05
MID, deg/s ↓	0.05	0.21	0.10	0.05
DVA, arc min ↓	10.5	67.4	37.0	16.8
DVA slope ↓	0.25	1.82	0.87	0.43
Log MAR acuity ↓	−0.18	0.07	−0.08	0.08
Log CS ↑	1.7	1.98	1.84	0.09
UFOV2, ms ↓	37	99	55.1	15.0
Expt Group				
Age	18	24	21.2	2.13
EXP	0.5	4	3.7	2.2
MDL, deg/s ↓	0.08	0.22	0.14	0.04
MID, deg/s ↓	0.05	0.18	0.13	0.07
DVA, arc min ↓	8.4	74.7	32.9	18.1
DVA slope ↓	0.20	1.52	0.83	0.46
Log MAR acuity ↓	−0.21	0.17	−0.03	0.11
Log CS ↑	1.5	1.92	1.77	0.11
UFOV2, ms ↓	30	77	46.4	12.9

motion, that is, looming.[3] The stronger relationship for the 3D motion test is consistent with previous research in aviation. For example, previous research has examined the relationship between scores on a variety of motion perception tests (including thresholds for MID and motion in the frontoparallel plane) and the performance of pilots in a flight simulator.[20] The MID thresholds were correlated significantly with landing and formation flight performance, while the relationships were not significant for the 2D motion test. Similar findings also were reported when real flight tasks were used.[19] Taken together, these findings suggest that 3D motion perception tests will be stronger predictors of performance on perceptual-motor control tasks involving approaching or receding motion and should be incorporated in test batteries for driving.

Unexpectedly, we also found a significant relationship between 2D motion perception and braking time. As discussed above, previous research has shown that 2D and 3D motion are processed relatively independently, a conclusion that is supported in our study by the nonsignificant correlation between MID and MDL test scores. Therefore, we did not expect these two tests to be related. One possible explanation could be that the 2D motion test used in our study was effectively a test of static VA, because a relatively small (7° × 7°), high density stimulus was used, while in the 3D motion test a large (40° × 36°), lower density stimulus was used. As discussed above, when high resolution stimuli are used, the relationship between motion perception and driving performance can be explained entirely by VA and contrast sensitivity.[8] However, in our study we did not find a significant correlation between VA and MDL test score, and furthermore, MDL was a significant predictor in the stepwise regression analysis. This issue is discussed in more detail below.

Another unexpected finding of experiment 1 was the lack of a significant relationship between the 2D motion tests and performance on the HP driving test. Given that our HP test involves lateral movement of objects (cars and pedestrians entering the roadway from the side), and that a significant relationship between 2D motion and HP has been shown in past research,[5,6] we anticipated that we would observe a similar relationship. Perhaps this effect was due to the complexity of the 2D motion test we used. While in previous research 2D motion tests involving simply indicating the direction of motion, our test required observers to identify letters. It will be interesting for future research to explore this difference. Another possibility is that the lack of relationship was due to the limited experience of the drivers in our study. It is possible that performance on the HP was determined more strongly by whether or not drivers had developed mental models of hazardous driving situations as opposed to motion perception. The significant positive correlation between HP test performance and years of driving experience is consistent with this idea.

Turning to the DVA test, a secondary goal of experiment 1 was to evaluate further a motion perception test with an eye movement component. As predicted, DVA thresholds in our study were correlated significantly with scores on the HP test. This finding is consistent with previous research.[5] However, expanding on previous research, we found that "velocity suscpetibility"[11] as quantified by the DVA threshold × target speed slope actually was a stronger predictor of HP test performance than DVA threshold alone.

Consistent with previous research,[22,25] we also found in experiment 1 that performance on the UFOV test was a significant predictor of HP performance. However, it should be noted that unlike in previous studies, our subjects were young and healthy without any cognitive or attentional impairments. One possible reason for this significant relationship is that the majority of the hazards used in our test involved a divided attention component (i.e., monitoring the position of other vehicles in central vision, while also monitoring the location of pedestrians and other vehicles in the periphery) like that assessed with the UFOV2 test. The fact that DVAs and UFOV were correlated significantly also is interesting. It is possible that the characteristics of visual attention measured with the UFOV test are a prerequisite for directing a subsequent eye movement.

Experiment 2

In experiment 2 we sought to test whether training on the motion perception tests used in experiment 1 would improve EB performance. Consistent with our prediction, the motion training group had a significantly greater reduction in braking time compared to the control group that received driving theory instruction. This finding suggests that improving motion perception through training can lead to safer driver behavior, namely quicker brake reaction time.

The mean difference between the control and experimental groups in the EB posttest was 0.17 seconds. While on the surface this may not seem like a large difference, the real world impact of a change of this magnitude can be seen by considering the effect of the Center High Mounted Stop Lamps (CHMSL) intervention. The CHMSL, also called the third brake light, has been standard equipment on all passenger cars sold in the United States since 1986 and all light trucks since 1994. The mandate for CHMSL was based on the technical evidence that braking reaction times were improved by an average of 0.11 seconds (range, 0.09–0.3 seconds).[26] Accident analyses subsequently have shown that CHMSL has resulted in a significant reduction in rear-end collisions and fatalities, and avoided several million dollars of property damage each year.[27,28] It will be important for future studies to investigate whether the effects on performance observed in the driving simulator in our study also result in reduced number of accidents in real driving, as has been shown for training designed to increase the speed of processing in a visual attention task.[25]

One important limitation of experiment 2 is the possibility that there could have been motivational differences between the experimental and control groups. Because several of the
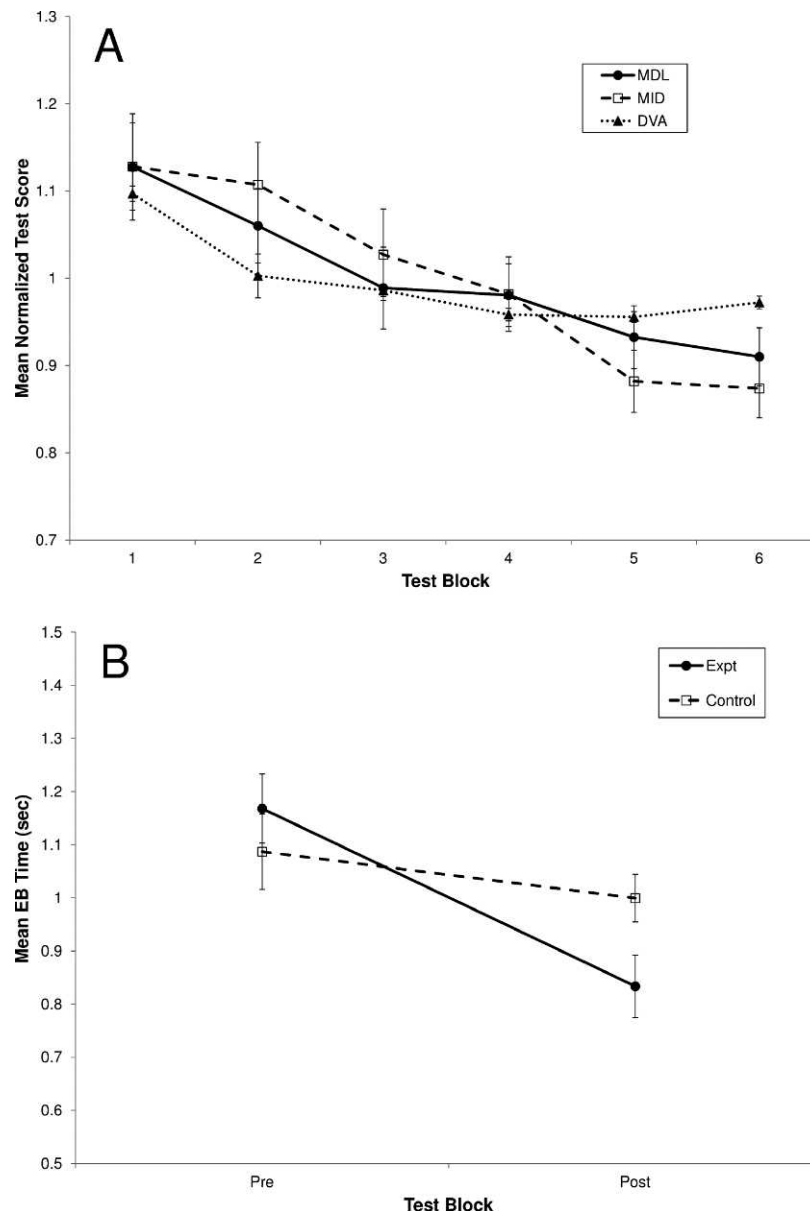
FIGURE 4. (A) Normalized motion test scores as a function of training block. (B) Mean total braking time in the pre- and posttests. *Error bars*: Standard errors. Scores were normalized by dividing by the mean score for each test.

drivers in our study had received their driver's license only relatively recently (which likely involved completing an online training course and tests similar to those used in our present study), the online training course may not have been particularly motivating. Conversely, the motion perception training is likely to have been more novel for our participants. It will be important for future studies to compare other types of control groups (e.g., training tests involving nonmotion perception, such as static acuity or UFOV).

General Discussion

The use of motion perception tests as possible predictors of driving performance and safety has been gaining momentum in the past decade with a handful of studies demonstrating relationships between the two.[7,9] The goal of our study was to expand on these efforts in two ways: expanding the content of the motion test battery and evaluating the feasibility of motion

perception training as a possible means to improve driving safety.

Given the importance of 3D motion perception[2] and eye movements[9] in driving, we hypothesized that the strength of the relationship between motion perception tests and driving performance would be increased if these two variables were incorporated better into the test battery. As discussed above, the majority of studies in this area have used only tests of 2D motion perception, with the one exception being a study in which driving performance/safety was not assessed directly.[18] While the motion perception tests that requires eye movements, namely DVA, have been used in past research in the area,[5] the relationship between DVA threshold and target speed ("velocity susceptibility"), which has shown to be important in other domains,[11] has not been examined in the context of driving to our knowledge.

Consistent with our hypotheses, the 3D motion perception test and our measure of velocity susceptibility (the DVA

threshold × target speed slope) along with the UFOV test, showed the strongest relationship with driving performance in our study. The MID test was correlated significantly with emergency braking performance, while the velocity susceptibility was correlated significantly with performance on a hazard perception test. Consistent with some past research, we also found that 2D motion perception was related significantly to our driving performance measures. Taken together, our study suggested that a motion perception test battery should incorporate tests of 2D motion, 3D motion, and DVA (with target speeds that are varied systematically) to maximize predictability. It is important to assess correlations among visual tests to avoid the use of overlapping/redundant tests in a clinical setting, or for administration of driver testing, where large numbers of individuals must be tested as quickly and efficiently as possible. Our results indicated that, while most of the vision tests were uncorrelated, VA and contrast sensitivity were correlated significantly, and DVAs and UFOV also were correlated significantly. The correlation between VA and CS is not surprising; however, the significant correlation between DVAs and UFOV was not expected. As noted above, it may be that deployment of visual attention to a peripheral location is important preceding an eye movement. This relationship could be of interest in further research.

Experiment 2 of our study provides evidence to suggest that motion perception training can have a positive influence on the driving behavior of younger drivers, namely reduced braking reaction times in response to a simulated potential collision. As can be seen in Figure 4B, a training program that involved repeating 2D, 3D, and DVA tests for 6 weeks resulted in a significant reduction in emergency braking reaction time that was not observed in a control group that received training in driver theory. Given that both groups completed the braking action the same number of times, we would argue that this difference was due to a change at the level of motion processing (e.g., greater sensitivity to looming) rather than at the motor response stage (e.g., faster foot movements from accelerator to brake). However, as discussed above, there also may have been motivational differences between the two groups. Therefore, it will be important for future research to investigate this type of training further (using other types of control/comparison groups) to determine to what extent this effect is due to improved motion perception and to what extent similar effects might be achieved with other types of training (e.g., contrast sensitivity or UFOV).

It also should be noted that the present training study involved young, healthy drivers. It will be important for future research to investigate motion perception training effects in individuals with compromised abilities resulting from ageing, ocular disease, or cognitive impairment. It is reasonable to assume that the training benefits may be even larger in these populations than those observed in our study, but of course that needs to be tested. Consistent with this idea, previous research has shown that one of the tests used in our present study (the MDL test) is sensitive to deficits in a variety of conditions for which standard VA is normal. These include amblyopia,[29] early enucleation,[30] multiple sclerosis,[31] and glaucoma.[32]

There are some important limitations to our study. First, it will be important for future research to expand the range of driving tasks used. It will be interesting to examine driving tasks that are associated with a high number of accidents and involve a strong 3D motion component, such as overtaking and passing,[33] and across path turns.[34] Second, it will be important for future research to use stimulus speeds that better represent those experienced in real driving. In our study, we chose to use values similar to those used in previous experiments[11,19] (e.g., 0.05 m/s for the MID test and 0.05–0.2 m/s for the DVA test) instead of trying to match the speeds to those experience in the driving task (11–15 m/s). Finally, as discussed above, it will be important to determine the effectiveness of motion perception training relative to other types of perceptual and attention training.

Conclusions

Previous research has shown that simple motion perception tests may be effective predictors of driving safety. The goal of our study was to expand on this work by evaluating the relative effectiveness of tests of 2D and 3D motion, and a motion perception test that involves eye movements, and evaluating the effect of motion perception training on driving performance. In terms of motion tests, it was shown that a 3D motion perception test was the best predictor of emergency braking, while DVA velocity susceptibility was the best predictor of hazard perception performance. In a second experiment, training on tests of motion perception resulted in a significantly reduced braking reaction time. This study provided evidence that incorporating motion perception tests in a test battery, including contrast sensitivity, color, and UFOV, would be far more predictive than existing screening methods, which rely almost exclusively on Snellen acuity, and in some instances, color and simple visual field tests. This study also providesd preliminary evidence to suggest that motion perception training may be a valuable tool in improving driver safety.

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